

Sustainable integration of lightweight expanded clay aggregate (LECA) in concrete for environmental resilience: A performance evaluation

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Promoting sustainability and green construction has gained more attention in society. This research has been focused on promoting sustainability and green construction by using lightweight expanded clay aggregate (LECA) as an alternative to natural coarse aggregates in concrete mixes. This approach has not only been promoted lightweight properties but also prioritized sustainability in construction, thereby minimizing the carbon footprint in the industry. The study has been focused on analyzing the physical properties of LECA aggregate and examined its porous structure and elemental characterization of LECA through scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis. Pre-soaking of LECA aggregate has resulted in enhanced workability, with an increase in slump and water absorption characteristics. In addition, the mechanical properties of LECA-infused concrete at 0, 25, 50, 75, and 100% with a grade of M25 have been analyzed, and a decrease in compressive, split tensile, and flexural strengths has been observed with increasing LECA content due to its high porosity and water absorption, which have impacted the density and strength parameters. The findings have shown that the addition of presoaked LECA has increased water absorption, sorptivity coefficient, chloride ion penetration, loss of mass, strength loss, and deterioration effects on acid and sulphate resistance. Furthermore, microstructural analysis has been carried out to ensure the microstructure and presence of essential chemical elements in LECA-infused concrete.

Keywords: Acid attack, Durability, Mechanical strength, Pre-soaking, Sulphate attack, Sustainability

1 Introduction

Concrete has been the most often used building material, with an annual production of approximately 10 billion m³ in the construction sector, which has highly relies on natural resources, especially aggregates such as sand, gravel, and crushed stone, as well as cement made from limestone¹. Large-scale mining operations have been required to obtain these resources, which have disrupted habitats and degraded land, thereby altering natural ecosystems². The quantity of resources that has been required to produce concrete alone has raised concerns about its long-term sustainability. Furthermore, the energy-intensive process used to produce cement has contributed a substantial amount to carbon dioxide emissions, which have aggravated climate change³. The combined consequences of these environmental repercussions have highlighted the necessity of producing concrete with greater care. Meanwhile, rapid infrastructure development and urbanization around the world have increased the demand for concrete, which has imposed additional strain on these natural resources⁴. The depletion of natural resources has not only

threatened the balance of ecosystems but also has impacted on the availability of necessary materials for upcoming generations⁵. As a result, it has become necessary to lessen the usage of these resources; therefore, it has become increasingly important to investigate substitute and environmentally friendly materials. Researchers have sought sustainable solutions to balance the demand for construction materials and preserve the integrity of ecosystems⁶⁻⁷.

Researchers have been exploring the possibility of substituting alternative and eco-friendly sources for concrete ingredients⁸⁻¹⁰. Normally, 70-80% of concrete volume has been composed of natural aggregate¹¹. Lightweight aggregates have drawn attention as a potential substitute for coarse and fine aggregate, based on previous research findings¹²⁻¹⁷. Two types of light weight aggregates have been distinguished: artificial light weight aggregates, such as artificial cinders, bloated clay, coke breeze, expanded shale and slate, sintered fly ash, expanded perlite, expanded vermiculite, and thermo Cole beads; and natural light weight aggregates, such as pumice, scoria, volcanic cinders, diatomite, perlite, and vermiculite¹⁸⁻¹⁹. Among these aggregates, lightweight expanded clay aggregate has

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grabbed the interest of researchers', and they have based their findings on its substitution for coarse and fine aggregate in different kinds of concrete²⁰⁻²³. The process of producing light weight expanded clay aggregate has involved heating natural clay in a rotary kiln to a temperature between 1150 and 1500 degrees Celsius. Because of the gas released during heating, the natural clay material has expanded around four to five times throughout the kiln process; for example, extracting one metric tonne of clay has yielded five metric tonnes of LECA aggregate²⁴.

Figure 1 has depicted the LECA aggregate production process. As a result of the kiln process, an aggregate in the shape of a round pellet with an internal black core, a hard, honeycombed structure, and interconnecting voids has been produced²⁵. For its numerous applications, the aggregate's size has ranged from 0 to 30 mm, while its density has fallen between 260 and 840 kg/m³. As a Green Alternative, innovative light Expanded Clay Aggregate (ECA) has emerged as an environmentally friendly solution for a variety of applications²⁶. Light weight expanded clay aggregate (LECA) or LIAPOR, has been produced under different product names in many countries. Brands such as "LECA" have been associated with countries like India, United Kingdom, Finland, Portugal, Iran, Denmark, Germany, Finland, and Switzerland; on the other hand, "keramzite" is associated with China, Russia, Sweden, and Poland. It has gone by the names "Argex" in South Africa and "Liapour" in Spain. LECA has shown strong commitment to the environment because the raw

materials needed for its production have been taken from the eco sources²⁷.

LECA material has been used in a variety of applications. Rawan Millah's²⁸ has suggested a comprehensive analysis utilizing LECA as a substrate in constructing wetlands. Furthermore, Lena Johansson's²⁹ research has provided promising results of utilizing LECA for phosphorus removal in wastewater within constructed wetlands. Additionally, Azhani Zukri *et al.*³⁰ have demonstrated the efficiency of LECA as a substitute material for conventional sand and aggregate in filling works, demonstrating its usefulness in geotechnical applications. According to Syukur *et al.*³¹, LECA has been used to assess the extent to which metals have been absorbed by it from acid tin mine drainage because of its porous medium and high absorption capacity³¹. In accordance with Roza *et al.*³², stearic acid has hydrophobized LECA stone, which has then been utilized in laboratory water tanks to lower water evaporation. In order to enhance the soft clays' bearing capacity under footing stress, Azhani Zukri³³ has looked into efficient replacement techniques, wherein LECA has been utilized as an alternative to common aggregate fillers. The load applied to the roof tops has been reduced when eco-friendly alternatives such as recycled coarse material and artificial light weight aggregates (LECA and incinerated municipal solid waste aggregate) have been used in the drainage layers and green roof substrate. Additionally, the thermal resistance, water permeability, and water extension capacity of the green roof layers constructed with these eco-friendly materials have been assessed by researcher Mostafa Kezemi *et al.*³⁴.

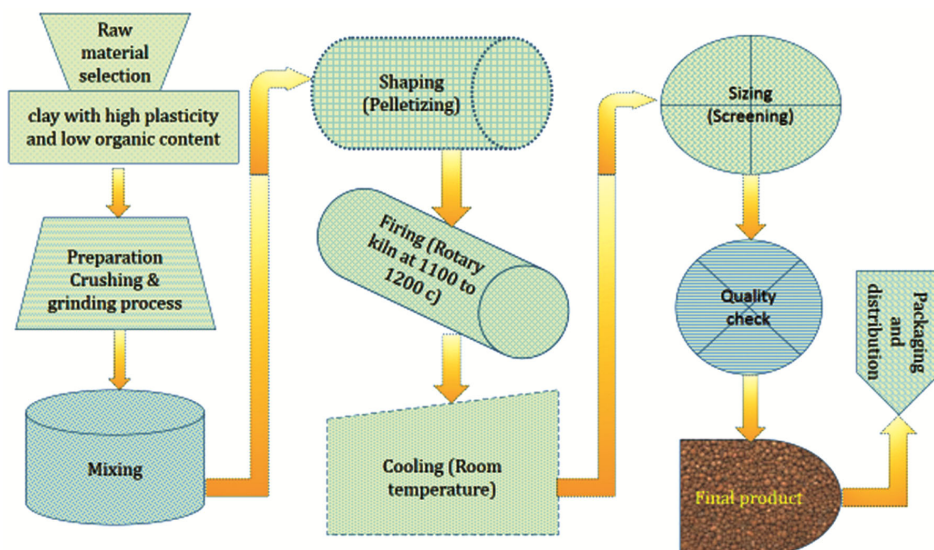


Fig. 1 — LECA aggregate production process.

According to Foriba *et al.*³⁵, LECA has been employed in acid-base treatment to remove the highly dangerous herbicide paraquat from the aqueous solution. According to Marek *et al.*³⁶, LECA has been added to the subsurface as an aiding layer with granulation of 1–4 mm in order to test its effectiveness in removing phosphorus and total nitrogen from wastewater. In the construction of buried pipelines, Barbara *et al.* have examined the effects of employing natural (earth backfill) and lightweight backfilling materials like LECA and recycled tire chips. These materials have had a beneficial effect on lowering the loads on the buried pipeline, which in turn has lowered the strains and deformation in its walls³⁷. Meanwhile several geotechnical uses, including light-weight sunken infill³⁸, embankment construction³⁹, retaining walls⁴⁰, landscaping⁴¹, agriculture⁴², horticulture⁴³, hydroponics⁴⁴, aquaponics⁴⁵, petrochemicals⁴⁶, and insulation for oil and gas bedding⁴⁷, have made use of LECA material. In addition to being used in geotechnical applications, LECA material has also been widely used in the production of various concrete formulations.

Researchers have now concentrated on using this lightweight material to create structurally strong, lightweight concrete for producing blocks and tiles, precast blocks, structural wall panels, and other products⁴⁸⁻⁵⁴. In terms of sustainable building approaches, the present study has explored a novel strategy that has incorporated lightweight expanded clay aggregate (LECA) as a strategic substitute for traditional coarse aggregate in concrete mixes. The primary objective of this research has been to carefully investigate the effects of replacing conventional coarse aggregate, either partially or entirely (0, 25, 50, 75 and 100%), with LECA. A key component of this investigation has been the thorough assessment of the strength and durability of the LECA concrete. The study has aimed to clarify the significance and durability of LECA-infused concrete as a sustainable building material by carefully examining these important characteristics. This examination has covered both the immediate mechanical strengths and the long-term durability features, which is in line with the overall objective of promoting sustainable construction practices. Furthermore, a microstructural analysis has been carried out to acquire an understanding of the material's sustainability performance. By investigating the possibility of LECA concrete as an environmentally friendly substitute, this study has contributed to the advancement of eco-conscious building practices.

2 Materials and Methods

Commercially available Portland pozzolana cement (PPC), which complies with IS 1489-1 (1991)⁵⁵, was utilized as the binder in the production of light weight aggregate concrete. PPC cement has a fineness of 320 m²/kg and a specific gravity of 3.14. Cement paste typically has a 32 percent consistency and requires 32 and 490 minutes to set initially and finally. Laboratory examination of the physical characteristics is conducted in compliance with Indian standards codal regulations (IS: 4031, part 2, 4, 5, and 11)⁵⁶⁻⁵⁹. In this investigation, locally sourced manufactured sand (M-sand) is used as fine aggregate. Similarly, 10mm of crushed coarse aggregate sourced from the local quarry is used. The specific gravity of M-sand is 2.59, and the fineness modulus is 2.39. M-sand has a water absorption of about 3.58 percent and a bulk density of 1680 kg/m³, respectively. Similar to this, coarse aggregate has a specific gravity and fineness modulus of 2.74 and 5.98, respectively. Coarse aggregate has a water absorption of 0.48 percent and a bulk density of 1590 kg/m³. The impact and crushing values of coarse aggregate are 23.2 and 34.5 percent, respectively. These laboratory examinations of the physical parameters are examined as per Indian standard codal provisions (IS: 2386 part 1, 3, and 4)⁶⁰⁻⁶², which also satisfy the requirements of IS 383⁶³. In this investigation, LECA which was purchased from the commercially available supplier is used as an alternative for conventional coarse aggregate in different proportions. Figure 2 (a–d), illustrates the materials used for making LECA infused concrete.

According to the Indian Standard Code (IS: 2386), the physical characteristics of LECA aggregate are analyzed and the fineness modulus of LECA aggregate is 5.96. Due to very less density, the specific gravity of LECA aggregate is 0.74. LECA aggregate absorbs water at a rate of around 15% because of its honey comb structure and interconnected voids. The bulk density of LECA aggregate, according to the laboratory analysis, is 290 kg/m³.

Figure 3(a) shows the microstructural analysis of LECA aggregate using a scanning electron microscope (SEM) with scanning scales of 2 and 10 μ m. The figure clearly illustrates the minute, large and interconnected voids present in LECA aggregate. It clearly shows that these are responsible for light weight and high absorption of water content. Figure 3(b) also shows the EDX analysis with the chemical characterization of



Fig. 2 — Materials used for making LECA infused concrete (a) PPC, (b) M-sand, (c) Coarse aggregate, and (d) LECA.

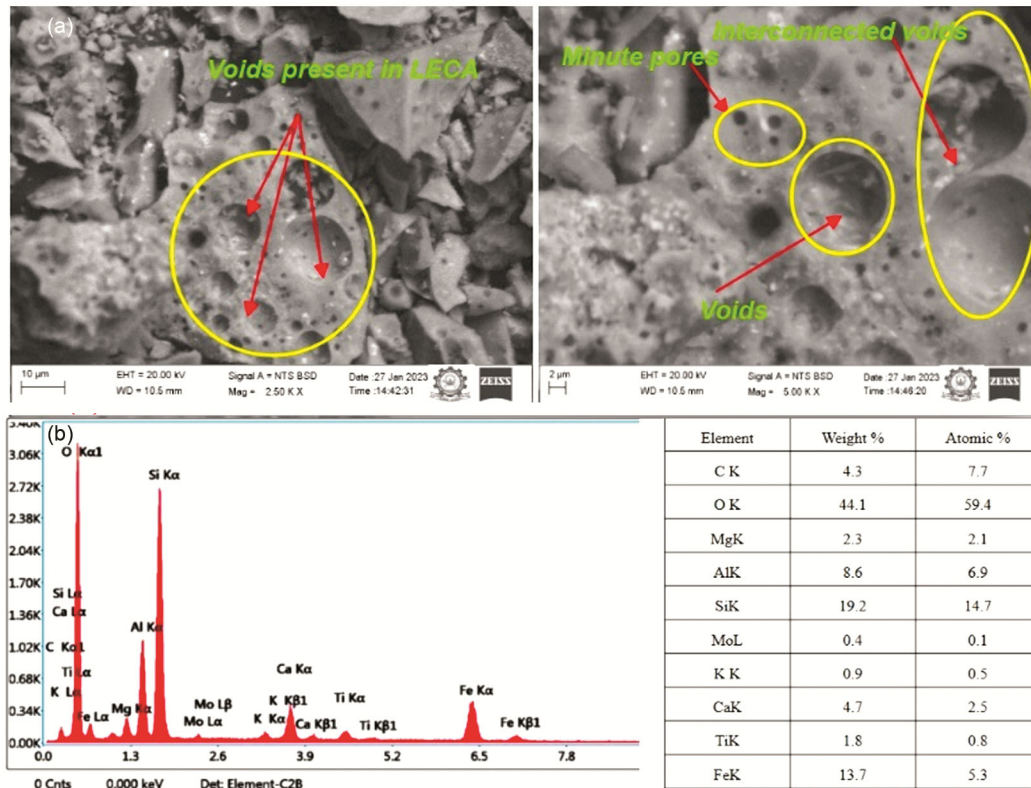


Fig. 3 — Microstructural and elemental analysis of LECA aggregate (a) SEM image showing surface morphology of LECA aggregate and (b) EDX analysis showing elemental distribution of LECA aggregate.

LECA aggregate. EDX analysis is mainly used to classify the elemental composition and type of minerals present in LECA aggregate. Furthermore, it is evident from the EDX results that 10 different compounds carbon (C), oxygen (O), magnesium (Mg), aluminium (Al), silica (Si), molybdenum (Mo), potassium(K), calcium (Ca), titanium (Ti), iron (Fe) are present in the LECA aggregate. A typical EDX spectrum containing the predominance of multi elements is shown in Fig. 3(b). Also the table mentioned in Fig. 3(b) lists, the elemental concentrations in weight and atomic (%) of LECA aggregate. The amount of elements present in weight and atomic percentage for carbon 4.3 and 7.7%, oxygen 44.1 and 59.4%, Mg 2.3 and 2.1%, Al 8.6 and

6.9%, Si 19.2 and 14.7%, Mo 0.4 and 0.1%, K 0.9 and 0.5 %, Ca 4.7 and 2.5 %, Ti 1.8 and 0.8%, Fe 13.7 and 5.3%, respectively. The major contribution of elements present in LECA aggregate with descending order shows oxygen, silica, iron, alumina, carbon, magnesium and titanium. Other elements with less trace composition were, magnesium, potassium, molybdenum and titanium are identified.

To evaluate the performance of LECA in structural concrete applications, M25 grade of concrete is used for designed mix proportion as per Indian standard IS 10262: 2019⁶⁴ and LECA aggregate is replaced with conventional coarse aggregate in proportions of 0, 25, 50, 75 and 100%. The detailed designed mix

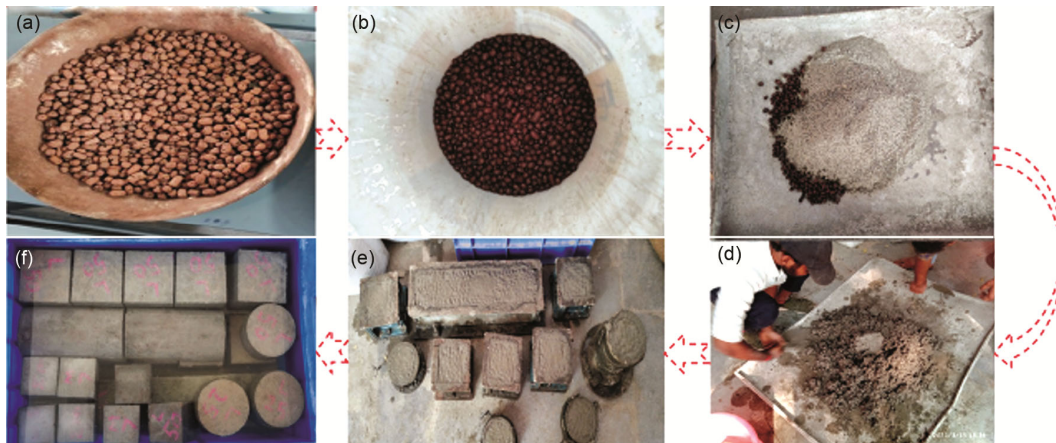


Fig. 4 — Casting and curing of (a) Dry LECA aggregate, (b) Pre-soaking LECA aggregate, (c) Transferring concrete ingredients into pan, (d) Manual mixing of concrete ingredients, (e) Transferring concrete mixture into moulds, and (f) Water curing of LECA infused concrete specimens.

Table1 — Designed mix proportions.

Mix identification	Replacement in (%)	PPC in (kg/m ³)	M-sand in (kg/m ³)	Coarse aggregate in (kg/m ³)	LECA aggregate in (kg/m ³)	Water in (kg/m ³)
LCS0	0	441	872	902	0	202.8
LCS25	25	441	872	690	61.75	202.8
LCS50	50	441	872	460	123.5	202.8
LCS75	75	441	872	230	185.25	202.8
LCS100	100	441	872	0	247	202.8

LCS0, LCS25, LCS50, LCS75, LCS100- LECA concrete specimen at 0, 25, 50, 75, 100% replacement.

proportioning for various replacements are illustrated in Table 1 and 0.46 was considered as the water to cementing ratio.

Before starting the casting process, LECA aggregate is presoaked in water for 24 hours due to its porous nature and it is wiped and air dried in cloth before mixing it in the concrete mixture. Remaining concrete ingredients are in dry state. Initially, the concrete ingredients PPC, M-sand, conventional coarse aggregate, and LECA aggregate are manually mixed at a consistent rate for each proportion mentioned in Table 1 to attain a uniform dry mix, and the quantity of water mentioned in Table 1 is added to the mixture to obtain a workable concrete mixture. Fresh concrete properties are determined with the prepared wet mix to ensure its workability. Cubes, Cylinders, beams and disc of size 100mm × 100mm × 100mm, 100mm × 200mm, 500mm × 100mm × 100mm and 100mm × 50mm are filled with the prepared wet mix and allowed to set for 24 hours. After 24 hours the concrete specimens are demoulded and placed in water curing for 28 days. The number of casted specimens for testing the strength and durability characteristics are illustrated in Table 2. Figure 4(a–f), shows the casting and curing process of designed mix proportioned concrete specimens.

The mechanical and durability test (compressive, split tensile, flexure, water absorption, sorptivity, rapid chloride penetration, acid and sulphate attack) are carried out to analyse the characteristics of each designed mix proportioned casted concrete specimen as mentioned in Table 2. The workability (fresh concrete characteristics) of LECA concrete is obtained by slump cone test as mentioned in Fig. 5 (a). Complying with IS: 516⁶⁵ and 5816⁶⁶, each designed mix proportioned casted cube and cylinder specimens (28 days curing) as indicated in the Table 2 was subjected to a uniform constant compressive load of 14 N/mm²/min and 2.4 N/mm²/min until the specimen broke in the compression testing machine (CTM) as demonstrated in Fig. 5(b–d). Furthermore, in compliance with IS: 516, beams undergone flexural strength testing on a universal testing machine (UTM) equipped with four point bending. Since LECA material is porous by nature, a water absorption test is performed to ascertain the absorption qualities. The purpose of this test is to assess how LECA concrete deteriorates when water penetrates through. Samples of LECA concrete cubes are cured for 28 days after casting in order to conduct this test. The samples that have been cured for 28 days are removed from the curing tank, gently cleaned with a cloth, and their wet

Characteristics	Table 2 — Number of specimens casted.		
	Specimen shape	No. of specimens casted	Age (days)
Mechanical			
Compressive strength	Cube	15	28
Split tensile strength	Cylinder	15	28
Flexural strength	Beam	15	28
Durability			
Water absorption	Cube	15	28
Sorptivity	Disc	15	28
Rapid chloride penetration test	Disc	15	28
Acid attack	Cube	15	28, 56 and 90
Sulphate attack	Cube	15	28, 56 and 90
Total number of specimens – 120			



Fig. 5 — Test carried out (a) Slump cone, (b) Compressive strength, (c) Split tensile strength, (d) Flexural strength, (e) Water absorption, (f) Sorptivity, (g) Rapid chloride penetration, (h) Acid attack, and (i) Sulphate attack, for LECA infused concrete.

weight is calculated and recorded as (W1). Following a 24-hour period at 110 degrees Celsius in a hot air oven as shown in Fig. 5(e), the specimens' dry weight is calculated as (W2). The weight % difference (W2-W1) from the initial weight (W1) is used to calculate the water absorption percentage.

The coefficient of sorptivity for the specimens listed in the Table 2 is assessed in accordance with ASTM C1585-04⁶⁷. Figure 5 (f) demonstrates the sorptivity test protocol. The specimens are shielded from water incursion along their sides and sealed along their thickness. To assess the rate of water absorption by capillary suction, specimens are positioned 5 mm above the water and left for 8 hours. To calculate the sorptivity coefficient (S), plot the cumulative water absorption per unit area of the

inflow surface (I) against the square root of time (t). The result is a measurement in $\text{mm}/\text{min}^{1/2}$.

$$S = I/t^{1/2} \quad \dots(1)$$

where t is the elapsed time in minutes, $I = \Delta W/Ad$, and $\Delta W = W2-W1$. The specimen's dry weight is represented by W1, its weight after 8 hours through capillary suction of water is represented by W2, its surface area through water intrusion is represented by A, and the density of water is represented by d.

Figure 5 (g) shows the testing procedure carried out on LECA-infused concrete disc specimens, as listed in Table 2, using the rapid chloride ion penetration test (RCPT), as described in ASTM C 1202⁶⁸ specifications. These specimens are subjected to a DC voltage of 60V for six hours using RCPT equipment and cell arrangement. The specimens are placed in the

equipment that contains two cell arrangements; one is filled with a 3.0% NaCl solution, and the other with a 0.3 M NaOH solution. The intended effect of the exposure to a DC voltage of 60V for six hours is to diffuse the chloride ions into the LECA concrete. After that, the current flowing through the LECA concrete is measured (Coulombs) at different intervals using a liquid crystal display (LCD) connected to the equipment. The equation used for calculating the average current across a single cell arrangement is $Q=900(P_0 + 2P_{30} + 2P_{60} + \dots + 2P_{360})$... (2)

where Q is the total current flowing through a single cell. P_0 is the current's initial ampere reading upon the application of voltage. P_t is the amp-reading of the current at time t min after the voltage application.

The cube specimens listed in Table 2 have been immersed in a solution containing sodium sulphate and hydrochloric acid (HCL) at a concentration of 2% for a period of 28, 56, and 90 days in order to assess their resistance to acid and sulphate attack as shown in Fig. 5 (h & i). It should be mentioned that during immersion, the pH of the solutions was maintained at or above 7. The cube specimens of the designed concrete mixes are removed after being immersed in HCL and Na_2SO_4 solution for 28, 56 and 90 days, and the corresponding weight loss and compressive strength values are observed. After that, a comparison with the control specimen, which was cured in water for 28, 56 and 90 days is used to calculate the percentage loss in weight and compressive strength. Using, SEM, and EDX, the microstructural properties of designed concrete mixes at 28 days of water curing and acid cured concrete are investigated. For the microstructural study, powdered samples of designed concrete samples are utilized.

3 Results and Discussion

3.1 Fresh characteristics

To illustrate the fresh properties of LECA concrete, slump test is carried out for each designed mix proportions and the workability of concrete is measured. Figure 6 shows the slump values of concrete with control mix and 25%, 50%, 75% and 100% LECA replaced concrete. The slump value ranges from 75 to 108mm with increase in 3%, 7%, 11%, 33% compared with control specimen. Various researchers have analysed the impact of lightweight aggregate replacement on the slump properties of concrete. Karthika *et al.*⁶⁹ replaced coarse aggregate with pumice aggregate at 50%, 80%, and 100%, reporting a slump

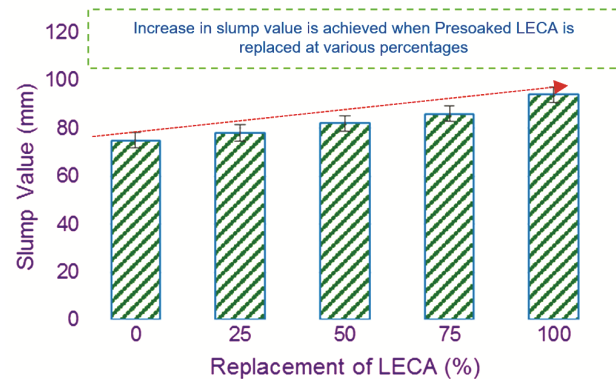


Fig. 6 — Replacement of presoaked LECA (%) versus Slump value (mm).

reduction of 69% to 76%. Similarly, Shafiq *et al.*⁷⁰ fully replaced coarse aggregate with pumice stone and observed an 11% decrease in slump compared to normal concrete. In contrast, Kockal *et al.*⁷¹ studied the influence of different lightweight fly ash aggregates on concrete behavior and reported a slump range of 150 mm to 165 mm, indicating improved workability. Likewise, Risdanareni *et al.*⁷² replaced coarse aggregate with sintered fly ash aggregate at 50% and 100%, achieving increased slump values of approximately 120 mm and 130 mm compared to conventional concrete. Overall, the effect of lightweight aggregate replacement on slump varies, with some studies reporting reductions while others show improvements. When compared to pumice stone replacement, presoaked LECA exhibits an increased slump at 100% replacement. However, in comparison to lightweight and sintered fly ash aggregates, presoaked LECA demonstrates a lower slump at 100% replacement, whereas fly ash aggregates yield higher slump values. The increase in slump value and good workable mixture of LECA infused concrete is achieved because of presoaking LECA aggregate in water.

3.2 Hardened characteristics

3.2.1 Compressive strength

Figure 7 shows the results of tests conducted at 28 days on the compressive strength of each specified mix proportioned specimens as listed in Table 2. The average compressive strength of control mix LCS0 is 35 N/mm² and LCS25, LCS50, LCS75 and LCS100 are 15, 12, 9.8 and 8.2 N/mm². Several studies have demonstrated the impact of replacing conventional coarse aggregates with lightweight aggregates on the compressive strength of concrete. The replacement of natural coarse aggregate with lightweight aggregates such as pumice and sintered fly ash aggregates has shown a considerable reduction in

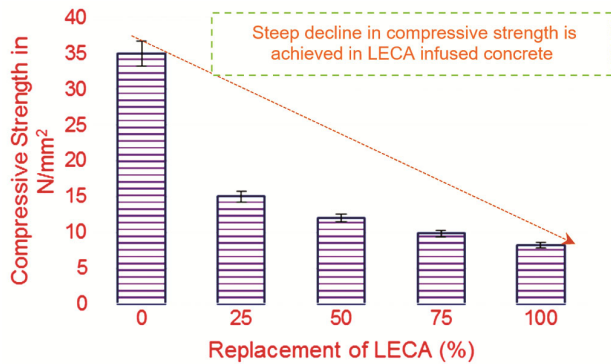


Fig. 7 — Replacement of presoaked LECA (%) versus Compressive strength (N/mm²).

compressive strength. Use of pumice stone as aggregate at replacement levels of 50%, 80%, and 100% resulted in strength reductions of approximately 68.2%, 73.8%, and 82.13%, respectively. Full replacement with pumice stone led to a 50% decrease in compressive strength at 28 days. Similarly, replacing coarse aggregate with sintered fly ash aggregate at 50% and 100% led to strength losses of about 16.87% and 32.8%, respectively. In another investigation, coarse aggregate was replaced with pumice aggregate at 25%, 50%, 75%, and 100% replacement levels, showing a gradual decline in compressive strength, reaching up to 68.42% at full replacement⁶⁹⁻⁷³.

While comparing these lightweight aggregates, LECA-infused concrete shows a declination in compressive strength for LCS25, LCS50, LCS75, and LCS100, and strength loss is around 57.14%, 65.71%, 72%, and 76.57%, respectively. Around 50% of strength gets reduced at 25% replaced LECA, and 77% of strength is reduced at 100% replacement of LECA. All these lightweight aggregates show a property of decrease in strength when it is replaced partially or wholly. As per the research findings and the current observations, when these aggregates are replaced above 25%, there occurs a strength loss of around 50%, and 80% strength loss is observed in all these types of aggregates when it is fully replaced for coarse aggregate. Only below 25% can achieve the designed target strength. This is attained because of the porous nature and low density of the aggregate.

3.2.2 Split tensile strength

Studies have shown that the replacement of natural coarse aggregate with pumice and sintered fly ash aggregates influences split tensile strength to varying degrees. When pumice aggregate was replaced at 50%, 80%, and 100%, reductions in split tensile strength of approximately 56.65%, 59%, and 67%

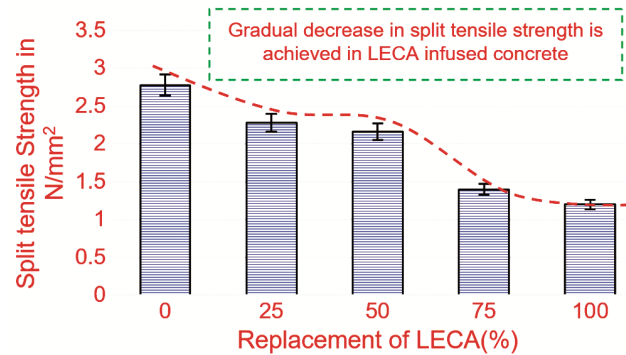


Fig. 8 — Replacement of presoaked LECA (%) versus Split tensile strength (N/mm²).

were observed. In contrast, whole replacement of coarse aggregate with pumice aggregate in another study resulted in only a 3.36% reduction compared to the control specimen. It has also been reported that the average split tensile strength is typically around 10% of the compressive strength, and no significant reduction was observed when coarse aggregate was replaced with pumice at 50% and 100% levels. Additionally, full replacement with sintered fly ash aggregate led to a decrease in split tensile strength of up to 46%. As compared with these past research studies, there occurs a reduction in split tensile strength when lightweight aggregates are used in concrete⁶⁹⁻⁷³. Similarly, when LECA is used in concrete, the average split tensile strength of control mix LCS0 is 2.78 N/mm², and LCS25, LCS50, LCS75, and LCS100 are 2.28, 2.16, 1.4, and 1.2 N/mm². There is a steady decline in split tensile strength of 17.98%, 22.3%, 49.64%, and 56.83% as compared with the control mix, as noted, and it is mentioned in Fig. 8.

3.2.3 Flexural strength

Arvind Kumar *et al.*⁷⁴ replaced fly ash aggregate up to 25% at an increment rate of 5% for coarse aggregate and obtained a gradual decline in the flexural strength, and the strength loss reaches up to 5.74%. As per the research, there occurs a gradual decrease in the flexural strength of lightweight concrete. As per the observations made on LECA-infused concrete, the average flexural strengths of LCS0, LCS25, LCS50, LCS75, and LCS100 are 5.12, 2.68, 2.42, 2.16, and 2.11 N/mm², respectively. When the research findings are compared with LECA infused concrete, a steep decline in flexural strength is achieved and the strength loss is also higher and it attains up to 58% at 100% replacement of LECA aggregate. The decrease in strength characteristics of

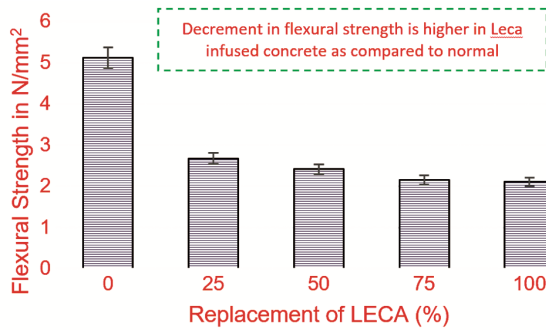


Fig. 9 — Replacement of presoaked LECA (%) versus Flexural strength (N/mm²).

LECA concrete is due to the lower density, the porous nature of the LECA material, the weaker bonding between the aggregate and cement paste matrix, and the higher moisture absorption in LECA concrete. Figure 9 shows the results of tests conducted at 28 days on the flexural strength of each specified mix proportioned specimens as listed in Table 2.

3.3 Durability characteristics

3.3.1 Water absorption

The water absorption properties of LECA-infused concrete after 28 days of curing are depicted in Fig. 10. Normal concrete exhibits a water absorption rate of 2.36%; while replacing LECA at 25%, 50%, 75%, and 100%, an increase in the absorption rate of 72.49%, 74.62%, 75.91%, and 80.3% is observed. This shows a direct correlation between the increase in LECA replacement and water absorption, with the highest absorption of nearly 80% occurring at full replacement. Similar trends have been observed in previous research studies on lightweight aggregates. When pumice stone was incorporated, the highest water absorption was recorded at 50% replacement, with an increase of about 61% compared to the control specimen. Likewise, the use of sintered aggregate and pumice stone in concrete leads to maximum water absorption at 50% replacement, showing an increase of approximately 45.93% and 54.39%, respectively. Compared to these findings, LECA replacement in concrete exhibits a more significant rise in water absorption, particularly at higher replacement levels, emphasizing its highly porous nature.

3.3.2 Density

The density of LECA concrete is depicted in Fig. 11. It is evident that a rise in LECA concentration causes concrete's density to drop. The weight of a typical concrete specimen is around 2.486 kg. When it is replaced to 25%, 50%, 75%, and 100%, the

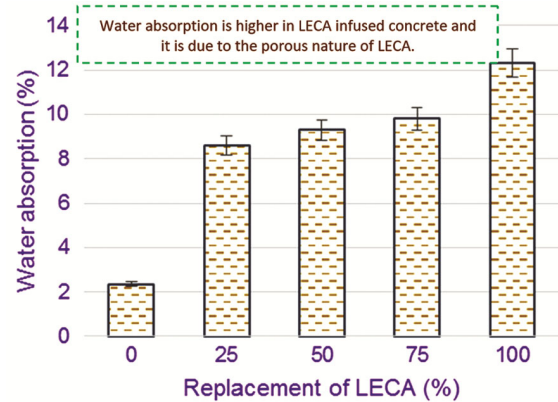


Fig. 10 — Replacement of presoaked LECA (%) versus Water absorption (%).

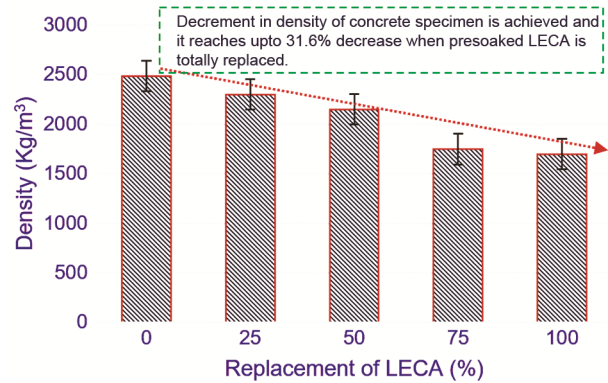


Fig. 11 — Replacement of presoaked LECA (%) versus Density (Kg/m³).

specimen's weight is approximately 2.3, 2.15, 1.75, and 1.7 kg, and its percentage ranges between 7.48%, 13.51%, 29.60%, and 31.6%. It demonstrates that specimens with 100% LECA aggregate replacement in concrete had a 31.6% lower density than specimens with normal concrete. This has occurred as a result of lower LECA aggregate density. Comparative studies on lightweight aggregates reveal similar trends. Replacement of natural coarse aggregate with sintered fly ash aggregate at 50% and 100% led to density reductions of approximately 9.2% and 23.72%, respectively, compared to normal concrete. Similarly, when pumice stone was used as a replacement for coarse aggregate at 25%, 50%, 75%, and 100%, the density reduction is 7.6%, 12.9%, 35%, and 49.2%, respectively. Among these lightweight aggregate concretes, LECA-infused concrete exhibits a more significant density reduction, around 32% lower than normal concrete. This pronounced reduction is attributed to the highly porous nature and lower density of LECA aggregates, making it a viable option for lightweight concrete applications.

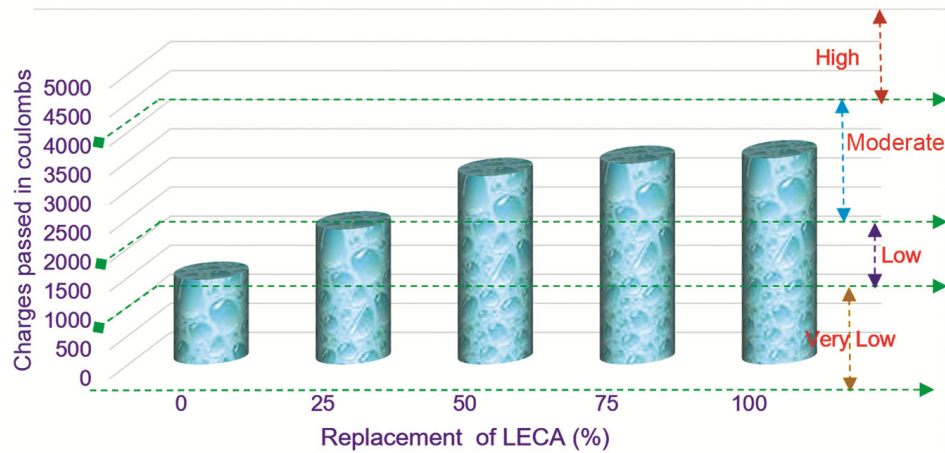


Fig. 12 — Chloride ion penetration analysis of LECA infused concrete.

3.3.3 Rapid chloride penetration test

The purpose of the chloride ion penetration test is to evaluate the resistance of concrete specimens to chloride ion penetration in order to ensure their durability⁷⁵. In order to prevent this issue in concrete, RCPT tests are performed on concrete samples. The chloride ions found in the environment have the ability to permeate concrete and start the corrosion of the reinforcing steel⁷⁶. Through the assessment of the concrete's resistance to chloride penetration, RCPT offers important information about how resilient it is against corrosive chemicals, ensuring the material's long-term durability⁷⁷. According to ASTM C1202 standards, Fig. 12 shows the relationship between the percentage of LECA replacement and the charges passed in coulombs. ASTM standards state that normal composition concrete specimens have low penetrability to chloride ions. However, according to ASTM specifications, experimental data show that substituting percentages of 25%, 50%, 75%, and 100% for LECA resulted in moderate chloride ion penetrability. This finding emphasizes how the porous nature of LECA aggregate allows chloride ions to penetrate and move through the concrete. As such, this property makes concrete that contains LECA inappropriate for use in marine regions. Under these circumstances, the presence of chloride ions presents a serious risk of corroding the structure's reinforcing steel, which might put at risk both the structure's structural integrity and general safety.

3.3.4 Sorptivity

The sorptivity coefficient serves as a key factor for evaluating concrete's resistance to water ingress, where lower values indicate better performance against moisture penetration⁷⁸. The total amount of water ingress

into the concrete specimens with different percentages of LECA aggregate through capillary action per unit area is shown in Fig. 13. A noticeable trend appears while examining the concrete specimens with varying percentages of LECA aggregate replacement.

For concrete with 25% LECA aggregate replacement, the sorptivity coefficient starts at a moderate level of water absorbance, measured at 3.42×10^{-5} . However, as the replacement percentage increases, the sorptivity coefficient shows a steady rise, reaching 6.85×10^{-5} and further to $18 \times 10^{-5} \text{ mm/min}^{0.5}$. This rising trend indicates that a decrease in resistance to water ingress, possibly due to the increased water absorbance capacity of LECA aggregate. Therefore, increased sorptivity coefficients suggest that water absorption by the concrete is increasing. Similar trends are observed for concrete specimens with 50%, 75%, and 100% LECA aggregate replacement, with initial sorptivity coefficient values of 2.57 , 4.28 , and $2.57 \times 10^{-5} \text{ mm/min}^{0.5}$ respectively. These values escalate to 17.14 and $21.43 \times 10^{-5} \text{ mm/min}^{0.5}$, indicating a progressive decline in resistance to water intrusion with higher LECA aggregate replacement percentages. Comparing these values to those of normal concrete specimens, it's evident that concrete with LECA aggregate replacement exhibits significantly higher sorptivity coefficients, ranging from 85% to 88% higher. This increasing trend suggests that the porous nature of LECA material leads to greater water absorption, raising concerns about the long-term durability of such concrete. The findings indicate that concrete containing LECA aggregate may not be suitable for applications where long-term durability is a primary concern, considering that it tends to have an increased water absorption compared to conventional concrete.

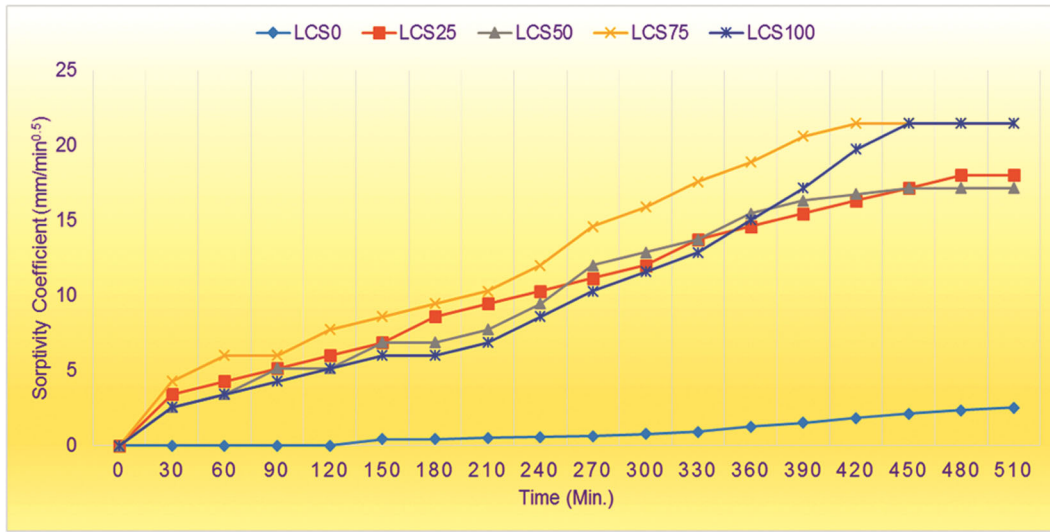


Fig. 13 — Sorptivity coefficient analysis for LECA infused concrete.

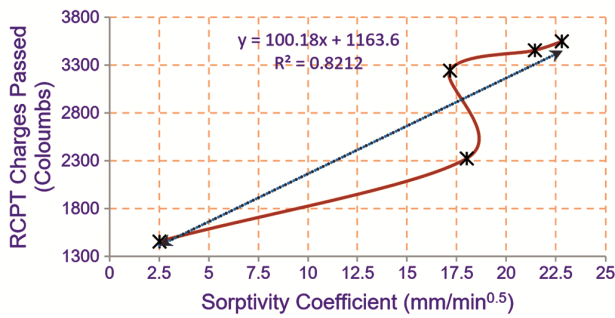


Fig. 14 — Correlation between RCPT and sorptivity coefficient.

3.3.5 Correlation between sorptivity coefficient and RCPT results

Figure 14 represent a scatter plot that shows the relationship between the sorptivity coefficient (mm/min) on the X-axis (how fast water is absorbed into concrete through capillary action) and the RCPT Charge Passed (Coulombs) on the Y-axis (how resistant the concrete is to chloride ion penetration; a higher value means less durability). The black dots represent the experimental data, and blue dotted lines show the best-fit linear regression equation, which helps to evaluate the correlation between sorptivity and RCPT. The regression equation obtained from the data is in the form of $A = Bx + c$, where A represents the RCPT Charge Passed (Coulombs), X represents the Sorptivity Coefficient (mm/ $\sqrt{\text{min}}$), B represents the Slope of the line, representing how much RCPT increases per unit increase in sorptivity, and C represents the Y-intercept, representing the RCPT value when sorptivity is zero. The coefficient of determination (R^2) is 0.82, which means that 82% of the variation in RCPT values can be explained by the

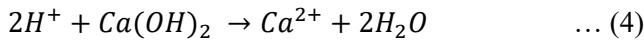
sorptivity coefficient. This indicates a strong positive correlation between the two parameters (if $R^2 = 1$, it would mean a perfect linear relationship & if $R^2 = 0$, it would mean no relationship). Since R^2 is close to 1 (0.82), it indicates that sorptivity is a strong predictor of chloride permeability in concrete. From the above observations, there is a strong correlation between sorptivity and RCPT values, which indicates higher sorptivity leads to higher RCPT values, which means concrete with higher capillary absorption is more vulnerable to chloride penetration. Concrete with lower sorptivity has better durability and lower RCPT values, which is a key strategy to enhance the durability of concrete structures exposed to chloride environments.

3.3.6 Acid attack and sulphate attack test

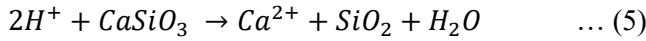
The acid and sulphate attack test is carried out to evaluate the long-term performance of concrete under aggressive environmental conditions⁷⁹. It demonstrates the chemical deterioration caused when concrete is exposed to acidic environment. When the concrete is immersed in hydrochloric acid (HCL), HCL dissociates completely into water to form hydrogen and chloride ions, then it starts reacting with hydration products of cement as mentioned in chemical equations 3, 4 and 5. The simple form of chemical reaction that occur within the concrete are explained below:



Where, HCl - Hydrochloric acid, H^+ - Hydrogen ion & Cl^- - Chloride ion

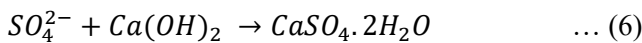


Where H^+ - Hydrogen ion, $Ca(OH)_2$ – Calcium Hydroxide, Ca^{2+} - Calcium ion & H_2O – water

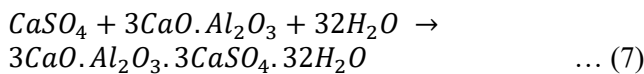


Where H^+ - Hydrogen ion, $CaSiO_3$ – Calcium Silicate, Ca^{2+} - Calcium ion, SiO_2 – Silicon dioxide & H_2O – Water

Reaction of calcium compounds with HCL leaches calcium ions which weakens the concrete that leads to the formation of cracks, voids and deterioration of concrete. Similarly, when the concrete is immersed in sodium sulphate (Na_2SO_4), it dissolves sodium (Na^+) and sulphate (SO_4^-) ions. These sulphate ions plays a key role in attacking the concrete components. When these sulphate ions react with the hydrated cement compound $Ca(OH)_2$, it tends to form $CaSO_4^{80}$. This $CaSO_4$ react with aluminates present in the concrete to form ettringite as shown in the chemical equations 6 and 7. The formation of ettringite and other sulphate components are responsible for volume expansion, crack formation, loss of strength and mass and deterioration of concrete⁸¹.



Where SO_4^{2-} - Sulphate ion, $Ca(OH)_2$ – Calcium Hydroxide & $CaSO_4 \cdot 2H_2O$ - Calcium sulfate dehydrate (Gypsum)



Where $CaSO_4$ – Calcium Sulphate, $CaO \cdot Al_2O_3$ – Tricalcium Aluminate, H_2O – Water, $CaO \cdot Al_2O_3$

$\cdot 3CaSO_4 \cdot 32H_2O$ - calcium sulfoaluminate hydrate (Ettringite)

Figure 15(a-b), illustrates the mass and strength losses resulting from exposure to HCL and Na_2SO_4 . The total mass loss for sulphate was seen to be 1-2% at 28 days, 2-3% at 56 days, and 2-5% at 90 days. This indicates a small decrease in weight compared to the original weight of the intended concrete LECA specimens. Likewise, for the HCL specimens, the total weight loss was found to be 0-1% for 28 days and 2-5% for 56 and 90 days. The compressive strength of normal concrete specimen, cured in water for 90 days, was observed to be 40.8 MPa.

When this normal specimen is exposed to Na_2SO_4 and HCL the strength loss is around 5.8% and 11.7%. In contrast, designed LECA concrete specimens shows a varying strength reduction when exposed to Na_2SO_4 , ranging from 5.8% for 25% LECA replacement to 16.5% for 100% LECA replacement. However, exposure to HCL resulted in more noticeable strength losses for LECA concrete specimens, with reductions ranging from 6.8% for 25% LECA replacement to 25.05% for 100% LECA replacement. These findings highlight a significant increase in strength loss when LECA concrete specimens are exposed to HCL compared to Na_2SO_4 .

The visual representation of designed LECA concrete specimens while conducting the acid and sulphate attack test at 28, 56 and 90 days are illustrated in Fig. 16(a) and it undergoes surface deterioration, characterized by erosion of the fine finished surface, resulting in a rough texture. Additionally, there was a change in colour of the specimen from grey to yellow. Salt deposition was

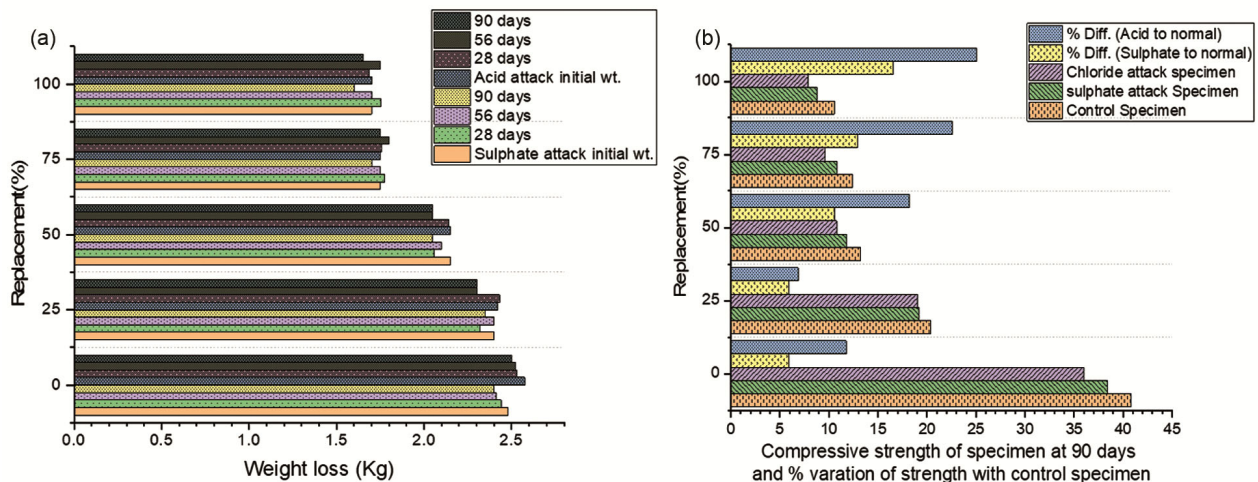


Fig. 15 — (a) Weight loss and (b) Compressive strength analysis of LECA infused concrete samples in acid and sulphate test

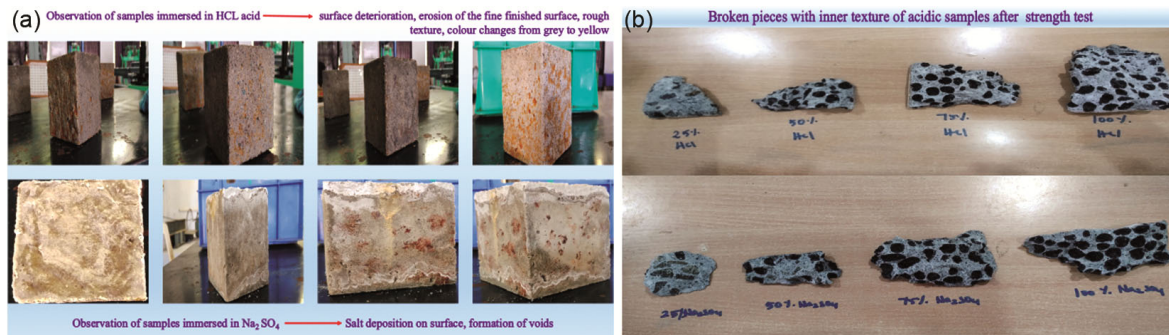


Fig. 16 — (a) Surface appearance of concrete specimens after exposure to acid and sulphate solutions, and (b) Visual inspection of inner matrix of samples after acid exposure and compressive loading.

observed on the surface, accompanied by the formation of voids and further deterioration of the concrete surface. Figure 16(b) shows the broken pieces of concrete specimens that were exposed to an acid attack and then subjected to a strength test. The internal texture of the broken pieces shows clear deterioration in the cement matrix and aggregates because of the harsh acid exposure. Concurrently, a decrease in both mass and strength was noted, further highlighting the adverse effects of acid and sulphate exposure on the concrete's durability.

3.4 Microstructural analysis

The microstructural characteristics of the concrete is analysed using SEM which provides valuable insights showing the importance of uniformness, compactness and the presence of specific crystalline formations⁸². In addition to that EDX analysis helps to understand the elemental composition of concrete, elucidate on the hydration process and its importance over concrete strength and durability⁸³.

3.4.1 SEM and EDX analysis

Figure 17(a-e), illustrates the observations made on SEM showing the surface morphologies of designed concrete mixes LCS0, LCS25, LCS50, LCS75, and LCS100. The scale of 10 μ m is used to examine the concrete samples and it reveals the presence of LECA material with pores and uniform spreading of concrete structure. The formation of calcium silicate hydrate, portlandite, silicon dioxide and ettringite are responsible for the strength characteristics of concrete in which the enhancement of strength is achieved with the presence of CSH, SiO₂, and ettringite crystalline structures and portlandite is responsible for decrease in strength.

Table 3 reveals the smart quantt results obtained during EDX analysis with elemental composition based on weight (%) present in all concrete samples

LCSS0, LCS25, LCS50, LCS75, and LCS100. The analysis unveiled the presence of elements across all concrete samples, that includes carbon (C), silicon (Si), oxygen (O), aluminum (Al), magnesium (Mg), sodium (Na), potassium (K), and iron (Fe). Carbon (C) is commonly found in cementitious materials and aggregates, contributing to the formation of calcium silicate hydrate (CSH) gel and the carbon content in normal concrete is 12.7%, whereas it decreases to 8.3% , 0%, and 9.2% with 25%, 50% and 75% replacement, marking a percentage difference of 34.6%,1%, 27.6% and obtained an increase in 24.4% in 100% replacement. (Si) present in the form of silicon dioxide contributes to the stability of concrete matrix and as per the table a noticeable increase in silica content (83.5%) is observed at LCS25 and LCS50 samples but decreases at LCS75 and LCS100 samples compared to LCS0.

Oxygen that surrounds everywhere in concrete is responsible for the formation of various compounds that includes CSH gel and calcium hydroxide⁸⁴. Oxygen remains relatively constant, with a slight increase of 0.4% at LCS25, gradual increase of 13.2% at LCS50 and a decrease of 4.4% at LCS75 samples as compared to LCS0. Cementitious materials contains aluminium (Al) as impurity which can influence the hydration process and mechanical properties of concrete. All content shows a gradual decrease in all concrete samples, showing a percentage difference of 46.9% and 48.4% at 75% and 100% replacement, respectively.

Additionally, some of the alkali elements like Magnesium (Mg) and potassium (K) which originates from cement and aggregates are responsible for the alkali-silica reaction (ASR) inside the concrete which can affect certain constituents in concrete and may influence in long term performance of concrete⁸⁵. As per table 3, Magnesium content rises significantly with replacement, reaching a percentage difference of 150%

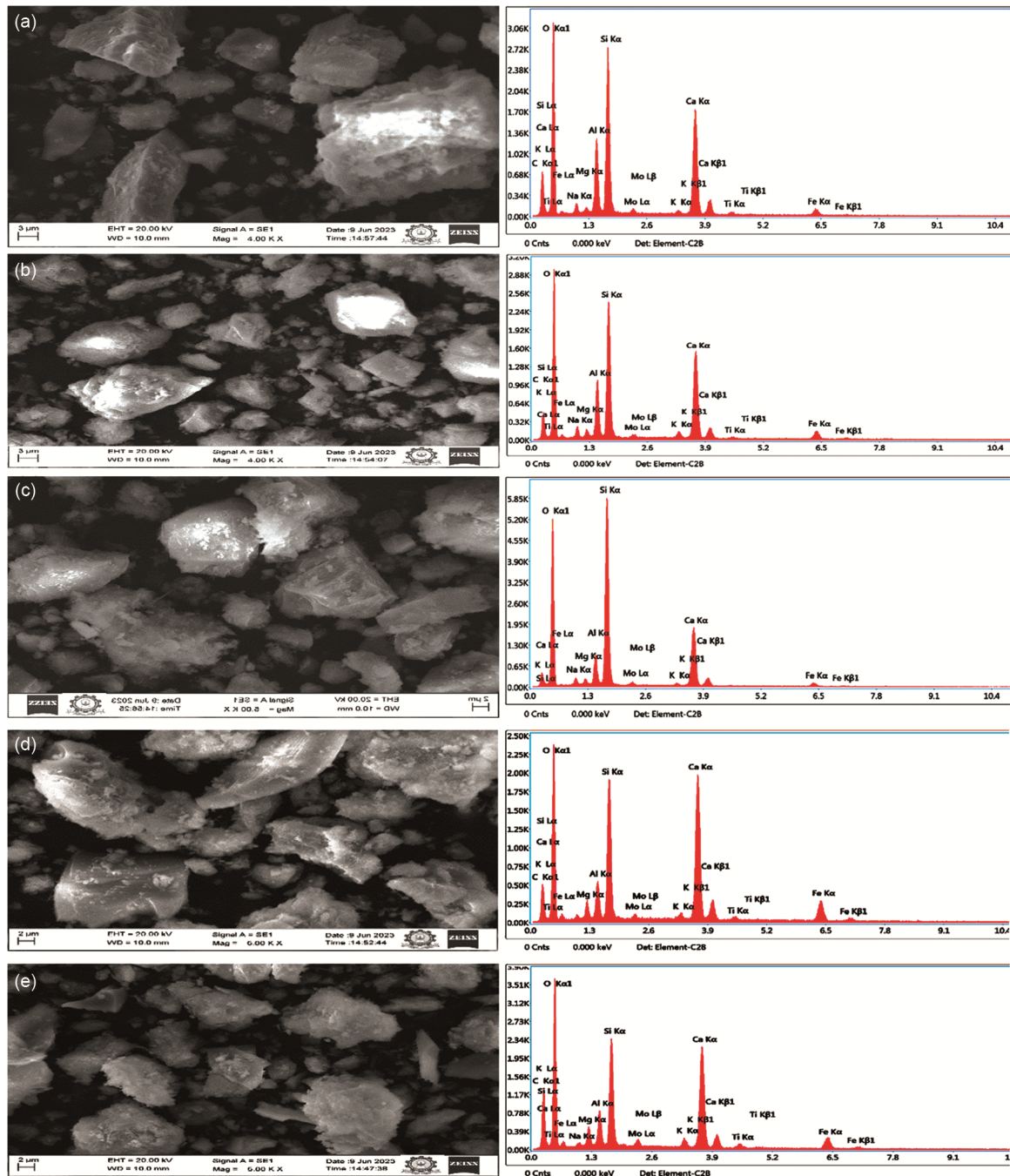


Fig. 17(a – e) — SEM and EDX analysis of LECA infused concrete showing the surface and chemical elements with (a) control specimen (LCS0), (b) 25% replacement of LECA aggregate (LCS25), (c) 50% replacement of LECA aggregate (LCS50), (d) 75% replacement of LECA aggregate (LCS75) and (e) 100% replacement of LECA aggregate, (LCS100).

at LCS75 and 175% at LCS100 compared to LCS0. Similar trend is achieved in presence of potassium alkali with increase in percentage up to 175% in LCS100. This can be solely responsible for the reduction in strength of designed LECA concrete samples.

Meanwhile sodium that is obtained from aggregates and cementitious materials play a significant role in the

process of setting time and chemical properties of concrete⁸⁶. As per EDX analysis shown in Table 3, Sodium content shows an increase of 29.4% and 23.5% at LCS25 and LCS50 respectively, while it decreases by 52.9% at LCS100 sample. The main component of hydration process is calcium which is highly present in portland cement is responsible for the strength and

Table 3 — Smart Quantt EDX analysis.

Element	Result in Weight (%)				
	LCS0	LCS25	LCS50	LCS75	LCS100
C K	12.7	8.3	-	9.2	15.8
O K	46.1	46.3	52.2	44.1	45.4
NaK	1.7	2.2	2.1	-	0.8
MgK	0.8	1.1	1.2	2.0	2.2
AlK	6.4	6.2	4.3	3.4	3.3
SiK	12.1	12.9	22.2	10.2	8.5
MoL	0.6	0.6	0.6	0.6	1.0
K K	0.4	0.9	0.4	0.7	1.1
CaK	16.3	17.1	15.1	21.9	16.7
TiK	0.6	0.5	-	0.8	0.9
FeK	2.4	3.8	1.9	7.0	4.3

durability of concrete. In this analysis, calcium content shows an increase of 4.9% and 34.7% at LCS25 and LCS75, respectively, while it decreases by 7.4% at LCS50 compared to LCS0.

Furthermore, iron (Fe) is typically found in EDX analysis can contribute to the coloring of concrete. Iron content varies significantly with all designed concrete samples, with a notable increase of 191.7% at LCS75 compared to LCS0. Additionally, trace amounts of manganese (Mn) and titanium (Ti) were detected, it decreases by 16.7% at LCS25 but increases by 33.3% and 50% at LCS75 and LCS100, although their concentrations are relatively low compared to the primary elements.

4 Conclusion

The following inferences are made using the results of this current study:

a. The physical properties of LECA material demonstrate its low weight, with a specific gravity of around 0.74 and a density of about 290 kg/m^3 , which is 82% less than that of natural coarse aggregate. This is because of the honeycombed structure of LECA, which allows it to absorb more water at a rate of about 15%. The elements and porous nature of the LECA material are revealed by the SEM and EDX microstructure investigation.

b. The slump of the designed mixes increases from LCS0 to LCS100, and it is around 33%, according to the designed mix proportion of M25 grade concrete. This indicates a good, workable mixture. The pre-soaking of the LECA material in water and its absorption rate are the reasons for the increase in slump.

c. The designed concrete mix specimens' compressive strength exhibits a decline in strength from the LCS0 to LCS100 sample. This indicates that

the presoaking method of LECA material can be substituted below 25% in order to acquire strength. Approximately 77% of strength is declined at LCS100, and 50% of strength declination is attained in LCS25. Comparing the split tensile and flexural strength characteristics to LCS0, declination of strength can reach up to 57% for split tensile strength and 58% for flexural strength.

d. High porous nature of LECA encourages high water absorption rate in all designed concrete samples in which the absorption rate ranges from 72% to 80% difference from LCS25 to LCS100 which can be the main reason for strength loss parameters. Meanwhile, the density of the specimen gets lowered up to 34% for LCS100 as compared to LCS0.

e. Due to the porous nature of LECA, the chloride ion penetration observed is moderate and it can't be suitable for the usage of material in marine regions. Similarly sorptivity coefficient reveals the porous nature of LECA aggregate with higher sorptivity coefficient.

f. Acid and sulphate attack reveals the loss in weight and strength of the designed concrete samples when exposed to HCL and Na_2SO_4 shows a reduction in loss up to 5% and strength loss up to 25% as compared to LCS0 on 90 days.

g. The microstructural analysis shows the texture and characterization of designed concrete samples and confirms presence of elements carbon (C), silicon (Si), oxygen (O), aluminium (Al), magnesium (Mg), sodium (Na), potassium (K), and iron (Fe). Carbon (C).

h. The future scope of work should concentrate on the reduction of water absorption capacity of LECA aggregate and improvement of strength and durability parameters of LECA infused concrete samples by adding some additive agents or cementitious material like silica fume, sodium silicate, ground granulated blast furnace slag, nano silica, metakaolin etc.

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